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Fast and accurate prediction of windborne contaminant plumes for civil defense in cities

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ABSTRACT: An instantaneous crisis management system called CT-Analyst®, based on detailed urban aerodynamics computations using Large Eddy Simulation (LES), has been developed, tested, and deployed to evaluate windborne Contaminant Transport (CT) threats and to aid in time-critical civil defense decisions in cities where current transport and dispersion methods are too slow and inaccurate. Designed for the military prior to 9/11, CT-Analyst can incorporate verbal reports, handle input from fixed and mobile sensors, and functions in realistic emergencies where the nature, amount, and location of an airborne contaminant source or Chemical, Biological, Radiological (CBR) agent is unknown and where the wind fields are dynamic and complicated by the city geometry. CT-Analyst is well suited to urban and site defense in the homeland Security context.

1 INTRODUCTION

Danger from airborne contaminants in cities, released in industrial accidents, spills, and fires or from the deliberate use of Chemical, Biological, or Radiological agents, motivates this work. A crisis manager or first responder will usually need to make immediate life and death decisions about how to respond to the airborne threat based on incomplete knowledge of the contaminant source. Even without their dire time constraints, determining wind-driven airflow over a city, accompanied by contaminant transport and dispersion, presents challenging modeling requirements (Boris, 2002; Britter & Hanna, 2003; Patnaik & Boris, 2010). Large, complex-geometry areas and unsteady buoyant flow physics drive computing needs to saturate current modeling capabilities so reasonably accurate runs take from hours to days. Crucial technical issues to be addressed include time-dependent turbulent fluid transport (urban aerodynamics), environmental boundary condition modeling (meteorology), and interaction of the winds with buildings (wind engineering). The advantages of Computational Fluid Dynamics (CFD) using the Large Eddy Simulation (LES) representation include quantifying complex geometry effects, faithfully predicting dynamic nonlinear processes, and reliably treating turbulent dispersion in regimes where experimental model validations are impossible or impractical. A companion paper in this volume, “FAST3D-CT: an LES model for urban aerodynamics” by Patnaik and Boris (2010), considers the performance and validation of such detailed, high-resolution computations. It also provides the background for this paper, which explains how to make such high quality answers available to crisis managers nearly instantly.

CFD solutions to CT can be highly accurate, but are too slow for emergency response and suffer other drawbacks including the need to specify a meaningfully complete initial condition. Therefore the crisis manager’s central dilemma of “fast **or** accurate” is usually framed by the negative questions: “How slow a run is too slow to be helpful in an emergency?” or “How

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inaccurate a prediction might still be acceptable?" As in the beer commercial, however, you can actually have both – speed and accuracy. There are applications where computation times of a few minutes or even a few hours might be acceptable but we concentrate on plume prediction applications where a few seconds, at most, is all the participants are really willing to wait. Further, there are important applications to multi-sensor interpretation and placement optimization that require even shorter computation times.

This paper is a brief review of the issues involved in meeting the seemingly contradictory requirements of speed and accuracy, more from a first-responder's perspective than a scientist's, and presents our methodology for bringing CFD-based results to the first responder quickly enough for emergency response. This new approach pre-computes three-dimensional urban wind-field databases for the specific region geometry using NRL's validated FAST3D-CT model (Young, et al., 1993; Boris, 2005; Kuzmin, et al., 2005; Patnaik and Boris, 2010). These runs include suitably parameterized weather, locally prevailing wind conditions, and a number of test sources. Special post-processing of these detailed wind-field databases allows us to summarize the information as *Dispersion Nomograf*™ datasets (Boris, 2002; Boris, et. al., 2002; Boris 2005) [1,6,8] that are fielded on small portable computers. The user software system implementing the nomografs is called CT-Analyst®[1,5,8] and extracts CFD-quality results from the nomograf database nearly instantly for use in crisis situations.

2 ACCURATE COMPUTATION OF URBAN AERODYNAMICS

The emergence of increasingly powerful computers stimulated the development of obstacle-resolving micro-scale flow and transport models based on CFD. These time-dependent models play an important role in many applications, serving as general tools in fluid dynamics, aerodynamics and wind engineering when complex flow systems have to be designed. Under the general category of Urban Aerodynamics (Boris, 2005), these models are now commonly applied to predict CT in complex-geometry urban landscapes. Use of such models is made in the licensing of new industrial plants, in safety analysis studies for accidental releases of hazardous materials in the chemical industry, or in the context of forensic analysis after accidents or terrorist attacks in urban environments. A discussion in some detail of NRL's FAST3D-CT three-dimensional urban aerodynamics model is given in the companion paper by Patnaik and Boris (2010) and ought not be attempted here. A practical example of urban-scale MILES computed with FAST3D-CT is illustrated in Figure 1 of the paper by Patnaik and Boris (2010) in this volume. It shows contaminant dispersion from a ground-level source at Rockefeller Center in New York City. The computational grid consisted of cubical 6-meter cells reaching above the average height of the buildings and which were then stretched vertically to about a kilometer over a four by four kilometer region.

Certainly the "speed-versus-accuracy" dilemma does affect CFD for these detailed urban aerodynamics simulations and considerable effort has gone into making FAST3D-CT fast. In particular the Monotone Integrated LES (MILES) turbulence approach is used in FAST3D-CT because of its high computational efficiency and ease of application in complex geometry. The chapters in Grinstein, et al. (2007) give recent reviews of this efficient methodology for modeling turbulence. It is sufficient to note here that 5-meter to 6-meter resolution LES computations for entire 100 square kilometer urban areas, such as illustrated in Patnaik and Boris (2010), can be completed in a day or two using only tens of processors on modern parallel computers. This is significantly faster per square km than other CFD models due to the savings achieved by MILES, parallelization, and other algorithmic improvements but it is still far too slow for crisis management and first responder use.

In an emergency, model results are not only required very quickly to be useful. They must often be generated from very incomplete initial data – not a situation conducive to the direct use of CFD or any other time integration model - no matter how efficient. In an accident, as well as a terrorist attack, we probably won't know exactly how much of what has been released or how quickly it is being released, even if we are lucky enough to know the point of origin. This means we must be able to proceed meaningfully without the missing information and we must be prepared to repeat the computations several times as more data becomes available. In a recent application of CT-Analyst, for example, the reported location of the contaminant source was in error by a few city blocks and only corrected after several minutes.

3 FAST AND ACCURATE CBR DEFENSE

Thus the *critical* dilemma in the CT application is that unsteady urban-scenario flow simulations are currently feasible – but they are computationally expensive and require special expertise to perform. First responders and crisis managers on site to cope with contaminant release threats have perhaps a minute altogether to make decisions and cannot afford to wait more than a few seconds while simulations and data post-processing are carried out either locally or remotely. Fortunately, we now have a methodology to make 3D CFD really useful for crisis managers in real time, operational situations. To resolve the speed-versus-accuracy dilemma, we carry out a few, large, unsteady CFD simulations well in advance, saving out compressed wind-field databases that incorporate the relevant meteorology for a full set of wind conditions, also computing a number of detailed test sources for each specific urban area to calibrate and validate the fast operational model. The CFD contaminant transport and dispersion databases are summarized as *Dispersion Nomograf*™ datasets to be used locally on portable computers. FAST3D-CT CFD underpins our current implementation of dispersion nomografs.

The implementation of this approach is called CT-Analyst® (Contaminant Transport Analyst). The nomograf representation makes a number of unique new capabilities possible (Obenschain, et al., 2004; Boris, et al., 2005) including sensor placement optimization and these are implemented in CT-Analyst. The methodology can also accept qualitative input and does not require knowledge of a source location or even a source type or amount. Thus sensor input and verbal reports can provide current information regarding the localized presence and absence of contaminants, their concentrations and winds. Thus a crisis manager can exploit the accuracy of CFD simulations nearly instantly with little loss of fidelity. Near instantaneous CT assessment with high-fidelity can reduce the number of people being exposed in urban areas, even for large crowds out in the open, by up to a factor of four or five once a simple sensor or reporting network is in place.

2.1 Nomograf Description: Nomografs**™** are compact, pre-computed data structures that capture the aerodynamic and turbulence effects of terrain, buildings, and vegetation on contaminant plume transport and dispersion. By interpolating into these nomografs, we can perform plume predictions and related assessments in milliseconds for wide areas with complex terrain such as cities, military bases, and important facilities. There are four distinct steps in generating and using dispersion nomografs:

1. An accurate geometry database for the region of interest is compiled from LIDAR, stereo imagery, or shape files. FAST3D-CT uses a two-dimensional (typically one meter

resolution) digital elevation map with the heights of terrain, buildings, trees, and surface composition in the computational domain as four arrays of integers.

2. Detailed 3D FAST3D-CT CFD calculations are performed over this composite geometry for 18 wind directions and the results are captured in an extensive database. These simulations include the appropriate urban boundary layer for the region with realistic turbulent fluctuations imposed at the inflow boundaries. Multiple releases are tracked in each run to calibrate and validate CT-Analyst.
3. The salient features from the CFD database are distilled into Dispersion Nomograf datasets for rapid interactive access. Time integration is thus replaced by interpolations that capture the aerodynamic effects of the urban geometry through the Nomograf tables.
4. The Nomograf tables are encrypted and input to CT-Analyst, an easy-to-use graphical user interface (GUI) for instantaneous situational analysis. Plume computation, for example, takes less than 50 milliseconds.

Three physical principles are central to the nomograf representation and its application: 1. Actual molecular diffusion plays only a minimal role. A contaminant transports dynamically via convection with the local airflow on all the important scales. 2. Wherever the contaminant goes becomes contaminated; a volume, once contaminated, is defined thereafter as contaminated. This is a conservative interpretation favored by first responders to aid in “safe siding” the predictions. 3. Vertical spreading of contaminant is quick on the building scale in an urban environment. Both simulations, e.g. Figure 1 in Patnaik and Boris (2010), and field trials support this approximation.

2.2 The CT-Analyst Crisis Management Tool: To exploit the dispersion nomograf technology, NRL developed Chemical-Biological-Radiological (CBR) crisis management software called CT-Analyst to solve the critical speed-versus-accuracy dilemma for time-constrained, information-limited users with real operational requirements. CT-Analyst is both instantaneous (meaning nearly zero computing delay) *and* accurate. CT-Analyst is visual, i.e., “point-and-click,” in application and deployable versions are implemented on laptops and workstations. The nomografs in CT-Analyst treat all of the buildings and structures in a multiple-square-mile downtown area, as illustrated in Figure 1 below, a screenshot from CT-Analyst for a 50 square-kilometer region of Baghdad. The influences of the building topography and the winds over the river are clearly seen to result in different plume shapes. In this example, four separate (fictitious) gaseous chlorine sources of different sizes have been released at different times and locations. The wind is from the WNW at about 6 m/s. CT-Analyst computes the integrated lethality effects for all sources simultaneously.

Each point in a domain of interest, if considered as a source location, has a downwind region called the footprint that can become contaminated by an airborne agent at that location. Any selected location (perhaps a site of interest) also has an upwind region (the danger zone) within which any contaminant released could contaminate that site. These two classes of regions are completely complementary, being effectively each other’s inverse. All assessments in CT-Analyst are “computed” by manipulating these two distinct regions for sensor report locations, for selected site locations, and for source locations. The nomograf representation is designed to make these manipulations very fast while requiring only a minimum amount of tabulated data for each wind direction. For the lower left source in Fig. 1 (5 tons released at 5 minutes), information from four notional sensors (the red and blue triangles) has been fused and analyzed by CT-Analyst to backtrack to an unknown source location (purple diamond region). For a particular site (purple square) in the center right, the upwind "danger zone," where a source could contaminate the site, is computed and shown in green and blue-green. The contour levels (black, purple, red, and yellow) actually displayed in the plumes in have been chosen to correspond to four levels of contaminant lethality for the inhaled gas.

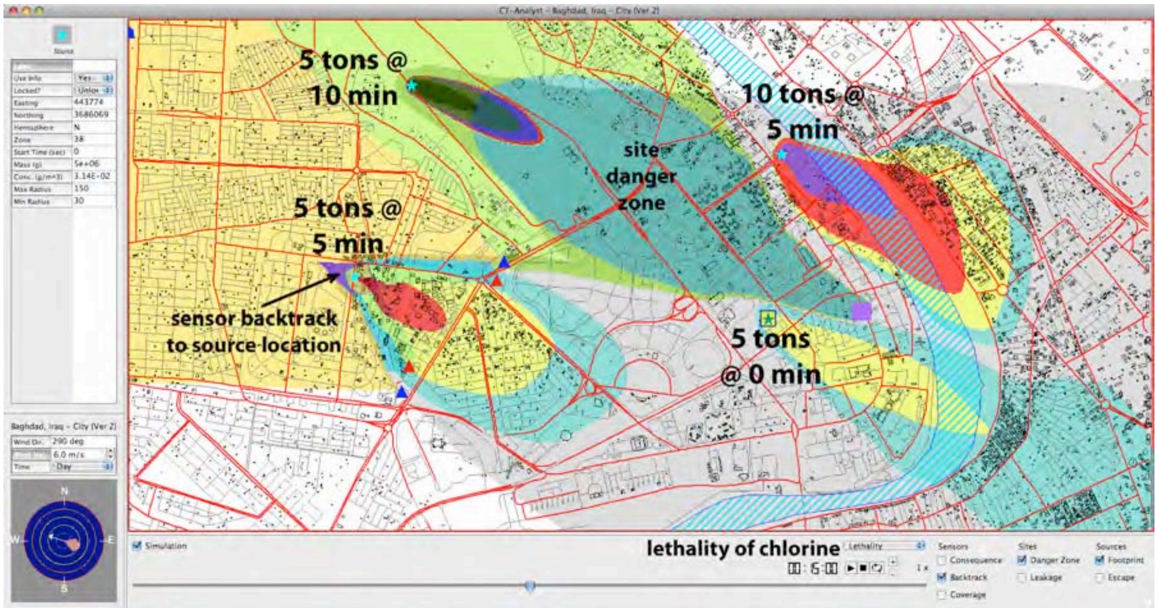

Figure 1. The entire CT-Analyst GUI display predicting lethality for a scenario involving four separate chlorine releases in downtown Baghdad. Notations have been added giving the amounts and release times of the four sources. Sensor fusion for a backtrack computation and a site danger zone are also shown. Computation for this composite display takes about 0.1 second.

By activating buttons on the lower portion of the display CT-Analyst can also compute plume footprints, envelopes, contaminant concentrations, and escape routes as a function of time for the sources. Downwind consequence regions (for active "hot" reports) and upwind backtrack estimates (for all active "hot" and "cold" reports) can be displayed for the active sensors, indicated by filled triangles. Contamination zones from down wind leakage and upwind danger zones can be plotted for different sites (green squares when uncontaminated and purple when contaminated).

Multiple sensor fusion for instantaneous situation assessment is an automatic consequence of the nomograf representation. A backtrack operation to identify unknown source locations is performed graphically with zero delay by overlap operations on the upwind danger zones of the "hot" and "cold" sensor reports. Furthermore, to compute danger zones, plume envelopes, and to backtrack, knowing the actual concentration of the airborne agent is not necessary. Indeed, until the total contaminant mass is known, plotting the actual concentration is impossible. Instead, CT-Analyst provides a relative concentration. The contamination footprints plotted by CT-Analyst are chosen to provide plausible worst cases; they are designed to "safe-side" the resulting situation assessments. This is an interpretation designed for first responders. In practice this means that any particular realization may only fill a part of the plume envelope depending on the structure of the wind gusts for that particular run. CT-Analyst attempts to indicate all regions that may be dangerously contaminated with a minimal degree of uncertainty.

4. VALIDATION

Significant bodies of validation work have been conducted on FAST3D-CT and CT-Analyst (e.g., Patnaik and Boris, 2010; Patnaik, et al. 2009, and references therein). An international DTRA-funded project compared detailed FAST3D-CT predictions with University of Hamburg wind-tunnel experiments and field-trial data from Oklahoma City. DHS supported a corresponding independent effort using field-trial data from New York City. The Missile Defense Agency, the Defense Threat Reduction Agency, and the Department of Homeland Security have also supported several independent validation (IV&V) efforts performed by outside agents. This validation, plus the operational deployment of CT-Analyst (Figure 4 below) has shown that CT-Analyst represents a significant step up over other available models.

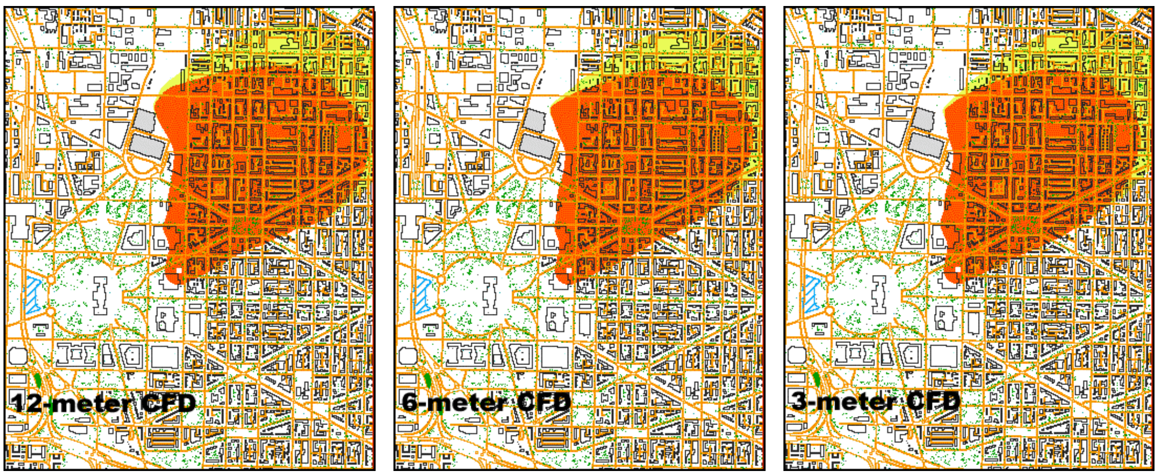

Figure 2. CT-Analyst display of a plume envelope for a release near Union Station in Washington DC using CFD computed at three different spatial resolutions. The orange regions show where the plume in is on the ground 6 minutes after being released at the small white square. The yellow region shows where the plume envelope extends above the ground but has not yet touched down.

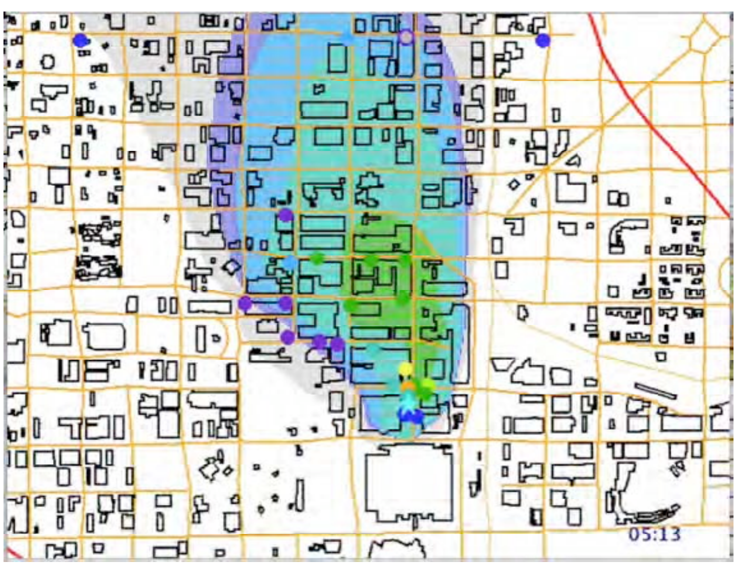

Figure 3. An instantaneous CT-Analyst tracer plume prediction for a point release in Oklahoma City showing agent concentration (green, blue-green, light blue, and violet contours) and the contamination footprint (grey) for a source at the light blue star. The field trial data from a single release (IOP-8) is shown as colored circles. A purple data circle indicates a SF6 tracer concentration thought to be below the threshold for detection.

Other previously unreported validation has also been performed. Figure 2 above shows three FAST3D-CT/CT-Analyst computations that show CFD grid-resolution convergence of the actual capability being deployed operationally for the 2009 Inauguration. The influence of the larger buildings at the train station is clearly seen at the upper left of each plume. Because the differences between the hazard areas shown are small, even the predictions based on 12-meter CFD will be accurate for a low spread-out city like Washington. A frame from a movie of field-trial data from Oklahoma City (colored circles) compared to CT-Analyst concentration contours is shown in Figure 3. The colors and extent of the measured and computed plume concentrations correspond quite closely. These comparisons represent a kind of instantaneous, visual validation of CT-Analyst. Comparisons between field trial data, FAST3D-CT simulations, and CT-Analyst predictions have been performed for regions of downtown Oklahoma City, New York City, and Los Angeles. However, there will always be room for more validation. Only by performing their own tests on CT-Analyst in their cities, will police, fire departments, and HazMat units gain confidence in the new tool, understand its limitations, and be familiar with its use.

5. CONCLUSIONS

By performing all the major computing ahead of time on large, high-performance computers, the results of high-resolution, dynamic 3D CFD simulations can be recalled for operational use with no sensible delay for integration of even simple models. Thus valid, physics-based answers are being presented instantly with full urban geometry in a readily understood, operationally deployed format for cities, bases, and other facilities. First responders, crisis managers, and warfighters can avoid both the delays and inaccuracies associated with earlier approaches to predict the spread of airborne contaminants. CT-Analyst not only gives greater accuracy and much greater speed than other models, it functions in information-starved situations such as characterize the first few minutes of a terrorist or accident scenario. Thus CT-Analyst provides important, new, real-time, zero-latency functions directly to the first responder such as sensor data fusion, backtracking to an unknown source location, and even evacuation route planning.

Figure 4. Hazardous Materials Reachback Center supports the Presidential Inauguration of 2009. Experts from a number of agencies came together at NRL to provide situation and consequence assessments for any real or postulated release of hazardous materials in Washington DC during the inauguration. CT-Analyst has also been delivered to local authorities in the cities of Chicago, Detroit, New York, Houston, Washington DC, and to other agencies in the Department of Defense. The Missile Defense Agency has incorporated CT-Analyst into its Post Engagement Ground Effects Model (PEGEM).

The computing and personnel resources needed to develop the Dispersion Nomografs that enable CT-Analyst are one-time but large costs. However, it is far better for scientists to wait for big computations well ahead of time than to have our crisis managers wait for results while hundreds or even thousands of people perish. Terrorist events are rare but CT-Analyst also applies to everyday incidents like fires and industrial leaks or spills. Further, the accumulated time saved by people involved in planning, site preparation, sensor optimization, and training, who now wait 10 to 15 minutes per scenario computed, is worth far more in dollars than the initial cost of the CFD to prepare the nomograf datasets. CT-Analyst is designed specifically for use where aerodynamic accuracy, i.e. building deflection and trapping of contaminants, must be combined with very rapid response (milliseconds rather than minutes). As a result, CT-Analyst was designated as the single crisis management model to be used for the first 30 minutes in any contaminant release incident occurring during the 2009 Presidential Inauguration, illustrated in Figure 4 above. CT-Analyst representations are currently being prepared for deployment in Los Angeles and Hamburg Germany, for automatic integration with meteorological wind fields (COAMPS), and for direct use in real-time simulation systems for training.

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